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COCKPIT THERMAL STRESS AND AIRCREW THERMAL STRAIN DURING ROUTIN--ETC(U)
MAR 79 T M GIBSON , L A COCHRANE
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ABSTRACT

Thermal data have been obtained from Jaguar aircraft flying routine, warm weather operations in Sardinia. These data have been analysed in terms of the ambient and cockpit wet bulb, globe temperatures (WBGT) and the mean body temperature (T_b) of the pilot.

In contrast to similar data previously obtained from Harrier and Buccaneer aircraft, no inter-relationships could be demonstrated between ambient WBGT at ground level and either cockpit WBGT or pilot T_b. Relationships, which could be described by equations of negative slope, were obtained between T_b and sortie time and between cockpit WBGT and sortie time. A model has been derived for predicting aircrew thermal strain in the Jaguar from cockpit temperature and sortie time.

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Previous reports have described the relationships between ambient, cockpit and pilot temperatures occurring during routine operational sorties flown in high performance aircraft and in helicopters (4, 7). Unfortunately, due to differences in the types of sortie flown and in the effectiveness of the cabin conditioning systems, the data upon which the mathematical analyses were based were highly variable; in addition, the measurements were made during generally cool conditions.

During 1978, similar measurements of ambient, cockpit and pilot temperatures were obtained in RAF Jaguar aircraft flying in Sardinia (5). These measurements were obtained when prevailing ambient temperatures corresponded to those expected during August in Germany. The data have been subjected to a similar mathematical analysis, using the same indices of ambient and cockpit thermal stress and pilot thermal strain. This paper describes the relationships between these indices for the Jaguar aircraft, and compares the present data with those obtained previously for both fixed wing and rotary wing aircraft (7). A comparison is also made between the present Jaguar data and those reported by Allan et al (1) for the F4E aircraft.

MATERIALS AND METHODS

A full description of the data collection and retrieval systems, and the experimental protocol followed during the investigation, can be found in the appropriate reports (6, 8). Measurements were made in 22 Jaguar sorties. The sorties were either routine range sorties (altitude <1230 m) or low level navigation exercises (altitude <615 m); air speed while airborne was between 240 and 420 knots. Sortie duration, which was dictated by the range timetable, was 30 to 40 min.

Measurements of Heat Stress. The following measurements were made on the ground adjacent to the aircraft taxiway:

1. Dry bulb temperature (T_{db}).
2. Ventilated wet bulb temperature (T_{wb}).
3. Black globe (50 mm) temperature (T_g).
4. Wind speed.

The following measurements were made in the aircraft cockpit during flight using a sensor cluster mounted just behind and above the pilot's right shoulder.

1. T_{db}.
2. Relative humidity (converted to T_{wb} by use of psychrometric tables).
3. T_g.
4. Air movement in the cockpit (V_w).

For the reasons discussed by Harrison et al (7) and to allow direct comparison with their results, the WBGT index was chosen as the index of thermal stress, as given by the equation

$$WBGT = 0.7\ T_{wb} + 0.3\ T_g\ . \qquad (1)$$

In 6 sorties, additional measurements were made of T_{db} at 5 sites using sensors mounted on the pilot's clothing. The sites were laterally on the middle of the right upper arm (T_{RA}), dorsally on the middle of the right forearm (T_{RF}), in the centre of the chest on top of one of the lobes of the life preserver (T_C), on the anterior surface of the right mid thigh (T_{RT}) and on the anterior surface of the right lower leg just below the leg restraint garter (T_{RL}). Comparisons were made of the arithmetic mean cockpit dry bulb temperature from these five sites ($\overline{T}_{db_A}$), a weighted mean ($\overline{T}_{db_W}$) and the single point measurement from the sensor cluster just behind and above the pilot's right shoulder. The weighted mean was calculated by the equation

$$\overline{T}_{db_W} = 0.35\ T_C + 0.20\ T_{RL} + 0.19\ T_{RT} + 0.14\ T_{RA} + 0.12\ T_{RF} \qquad (2)$$

which gives a contribution from each sensor which relates to the local body surface area as described by Allan et al (1).

Measurement of Heat Strain. Deep body temperature was measured using a thermistor in the external auditory canal close to the ear drum (T_{ac}); mean skin temperature ($\overline{T}_{sk}$) was calculated as a weighted mean of skin temperatures from thermistors placed at 4 sites (10). Heat strain has been assessed in the same way as Harrison et al (1) to allow direct comparisons to be made. Thus mean body temperature (T_b) is given by the equation

$$T_b = 0.8\, T_{ac} + 0.2\, \overline{T}_{sk}. \tag{3}$$

Data Collection and Analysis. Ambient conditions were measured next to the aircraft taxiway immediately before and after each sortie, and the WBGT index was calculated using a mean of these measurements. Aircraft cockpit conditions and pilot body temperatures were measured automatically during each sortie; the indices of stress and strain were calculated from measurements made every second minute between take off and landing.

Relationships between ambient, cockpit and pilot temperatures, and between sortie duration and cockpit and pilot temperatures were examined by regression analysis. Possible relationships between the following variables were considered:

1. Mean cockpit WBGT and ambient WBGT.
2. Mean pilot T_b and ambient WBGT.
3. Pilot T_b and cockpit WBGT.
4. Cockpit WBGT and sortie time.
5. Pilot T_b and sortie time.
    a. T_{ac} and sortie time.
    b. $\overline{T}_{sk}$ and sortie time.
6. Cockpit temperatures and V_w.
7. T_{db}, $\overline{T}_{db_A}$ and $\overline{T}_{db_W}$.

In these analyses, a regression line was fitted for each sortie, and r^2 was calculated. The regression lines were then compared for slope and intercept. The mean slope (m) and mean intercept (c) with their standard errors (se_m and se_c) were calculated and the significance of the difference of overall mean slope from zero was established.

RESULTS

The individual results for each of the 22 sorties have been reported separately (5).

1. Cockpit and Ambient WBGT. Values of $WBGT_{cockpit}$, averaged over each aircraft sortie, did not correlate significantly with the mean of ambient WBGT values measured at ground level immediately before and after each aircraft sortie.

2. Pilot T_b and Ambient WBGT. The average pilot body temperature for each sortie did not correlate significantly with the mean of ambient WBGT values measured immediately before and after each sortie.

3. Pilot T_b and Cockpit WBGT. Regression analysis yielded the following relationship between pilot T_b at any time between take off and landing and cockpit WBGT at the same time:

$$T_b = 36.17 + 0.033\ WBGT_{cockpit} \qquad (4)$$

($0.03 \leqslant r^2 \leqslant 0.74$ for 13 sorties; $se_m = 0.006$, $P < 0.001$; $se_c = 0.18$; Fig 1).

In one sortie, the cabin conditioning system failed immediately after take-off and this sortie was therefore analysed separately. In this case, the relationship (which proved statistically significantly different from that described by equation (4) at the 0.1% level) was as follows:

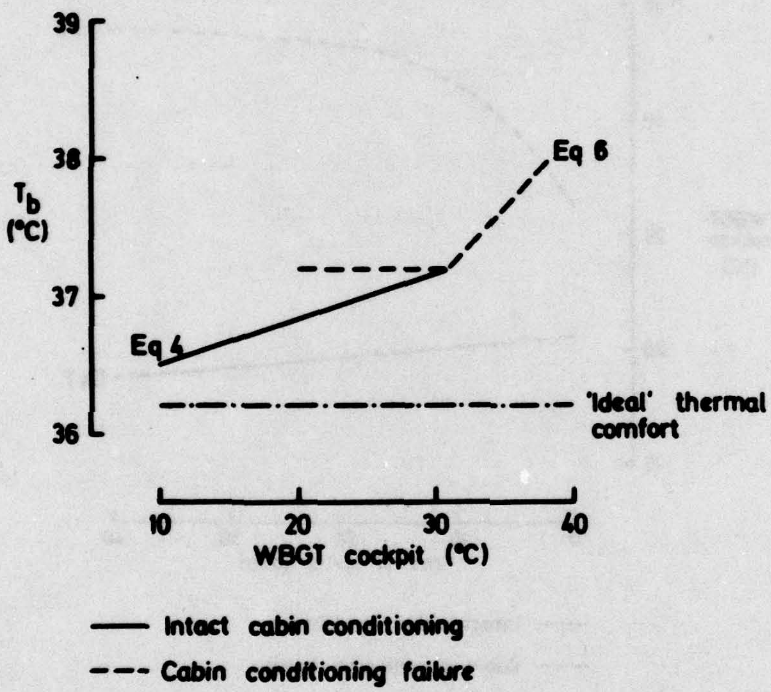

Figure 1 Relationship between cockpit WBGT and T_b.

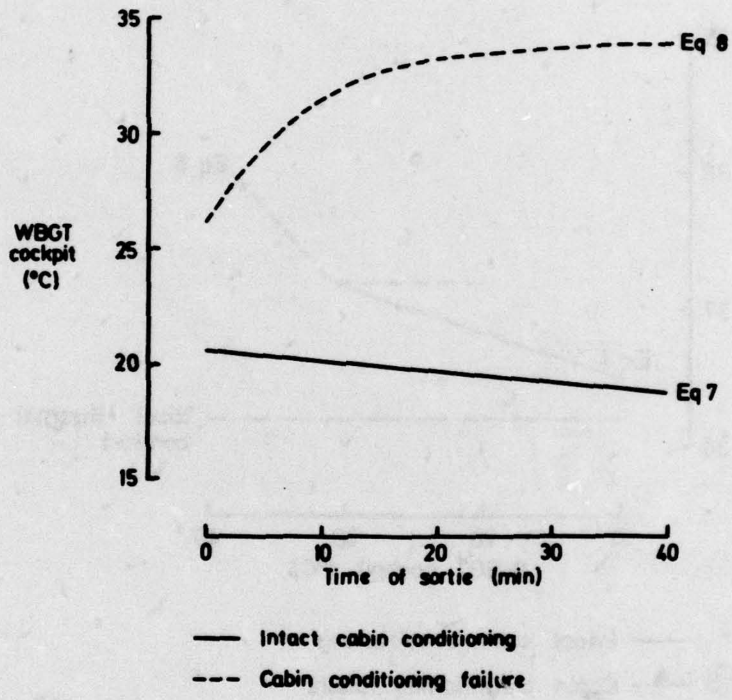

Figure 2 Relationship between cockpit WBGT and sortie time.

$$T_b = 35.75 + 0.051\ \mathrm{WBGT}_{cockpit} \tag{5}$$

$$(r^2 = 0.60 \text{ for } n = 20,\ p < 0.001),$$

although a split regression of the form

$$T_b = 37.20 \text{ (for } 25 \leq \mathrm{WBGT}_{cockpit} \leq 31)$$

and $$T_b = 37.20 + 0.110\ (\mathrm{WBGT}_{cockpit} - 31.0)$$

$$(\text{for } 31 \leq \mathrm{WBGT}_{cockpit} \leq 35;\ \text{Fig 1}) \tag{6}$$

gave a better fit.

4. <u>Cockpit WBGT and Sortie Time</u>. Cockpit WBGT fell between take-off and landing, as follows:

$$\mathrm{WBGT}_{cockpit} = 20.57 - 0.044\ t \tag{7}$$

($0.00 < r^2 < 0.66$ for 13 sorties; $se_m = 0.018$, $P < 0.01$; $se_c = 0.54$; Fig 2), where t is the time in minutes.

When the aircraft was parked with the canopy open, cockpit WBGT was the same as ambient WBGT. When the canopy was closed, $\mathrm{WBGT}_{cockpit}$ rose by 4.22 ± SD 0.47°C by the time of take off. When the cabin conditioning was switched on immediately after take off, cooling to the level described by equation (7) generally took place within 2 min and always within 5 min. During landing, the cabin conditioning system was switched off, and cockpit WBGT increased 2.20 ± SD 0.53°C before the canopy was closed. In the one sortie where the cabin conditioning system failed, $\mathrm{WBGT}_{cockpit}$ rose exponentially during the sortie; the relationship was expressed by an equation of the form $y = a + b.e^{-dx}$ as follows:

$$\mathrm{WBGT}_{cockpit} = 33.76 - 7.66\ e^{-0.1117t} \tag{8}$$

$$(r^2 = 0.91 \text{ for } n = 20,\ P < 0.001;$$

$$se_a = 0.37;\ se_b = 0.60;\ se_d = 0.0218;\ \text{Fig 2}).$$

5. <u>Pilot T_b and Sortie Time</u>. Pilot T_b tended to fall between take-off and landing; regression analysis gave the following relationship:

$$T_b = 37.00 - 0.010\ t \tag{9}$$

($0.00 < r^2 < 0.98$ for 14 sorties; $se_m = 0.0025$, $P < 0.01$;

$se_c = 0.07$; Fig 3).

When the components of T_b were studied in further detail, no significant relationship was found between T_{ac} and sortie time (the slopes were negative in 5 sorties and positive in 9). Mean skin temperature varied with sortie time as follows:

$$\overline{T}_{sk} = 34.73 - 0.056\ t \tag{10}$$

($0.01 \leqslant r^2 \leqslant 0.96$ for 14 sorties; $se_m = 0.009$, $P < 0.001$;

$se_c = 0.22$; Fig 3).

In the sortie where cabin conditioning failed, T_b was related to sortie time as follows:

$$T_b = 37.13 + 0.012\ t \tag{11}$$

($r^2 = 0.90$ for $n = 20$, $P < 0.001$; Fig 3).

The components of T_b, (T_{ac} and $\overline{T}_{sk}$), were related to sortie time as follows:

$$T_{ac} = 37.32 + 0.009\ t \tag{12}$$

($r^2 = 0.79$ for $n = 20$, $P < 0.001$

and

$$\overline{T}_{sk} = 36.40 + 0.019\ t \tag{13}$$

($r^2 = 0.87$ for $n = 20$, $P < 0.001$; Fig 3).

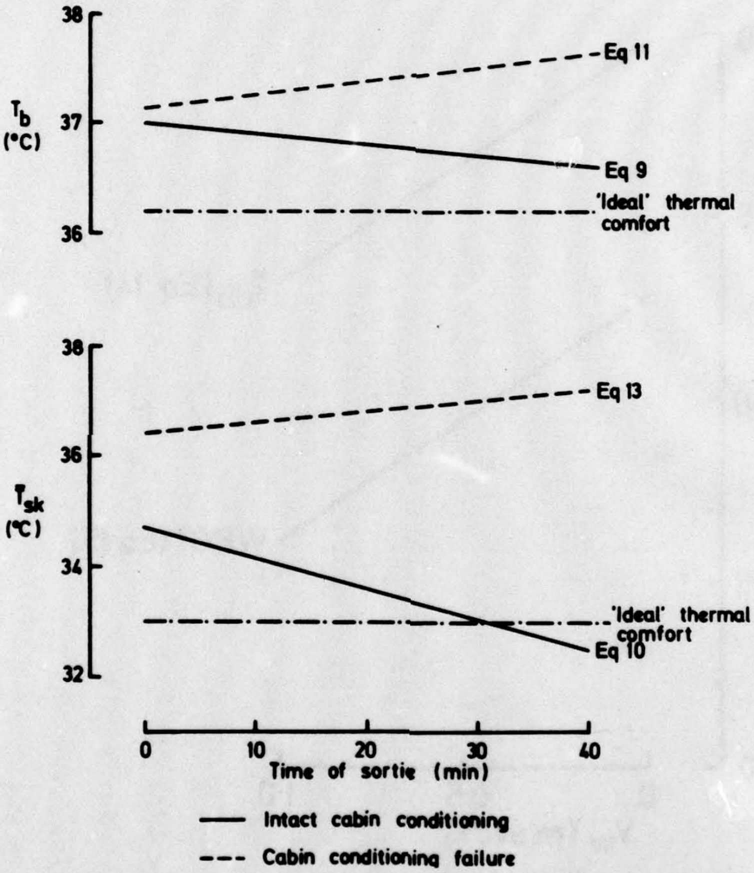

Figure 3 Relationship between T_b and $\overline{T}_{sk}$ and sortie time.

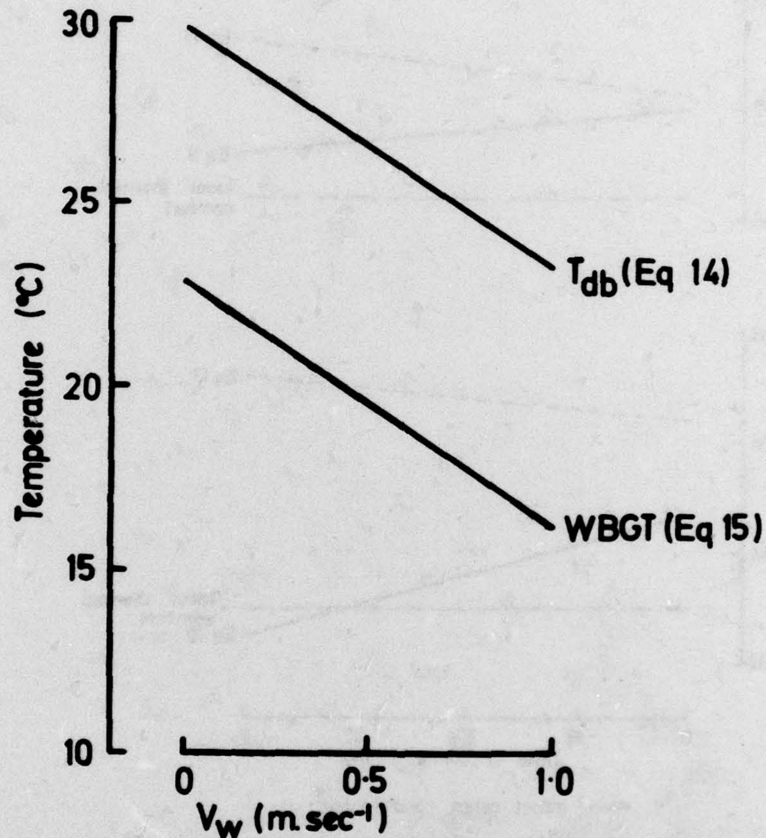

Figure 4 Relationship between cockpit T_{db} and WBGT and cockpit air flow.

6. Cockpit Temperatures and V_w. The relationships between cockpit temperatures and cockpit V_w were as follows:

a. $$T_{db} = 29.79 - 6.53\ V_w \tag{14}$$

($0.00 \leqslant r^2 \leqslant 0.65$ for 16 sorties; $se_m = 1.40$, $P < 0.001$; $se_c = 0.90$; Fig 4).

b. $$WBGT_{cockpit} = 22.83 - 6.63\ V_w \tag{15}$$

($0.03 \leqslant r^2 \leqslant 0.59$ for 16 sorties; $se_m = 1.71$, $P < 0.01$; $se_c = 0.84$; Fig 4).

c. There was no statistically significant relationship between T_g and V_w.

7. T_{db}, $\overline{T}db_A$ and $\overline{T}db_W$. The arithmetic mean dry bulb temperature was related to the single point measurement of cockpit T_{db} in the following manner:

$$\overline{T}db_A = 4.36 + 0.834\ T_{db} \tag{16}$$

($0.40 \leqslant r^2 \leqslant 0.83$ for 5 sorties; $se_m = 0.07$, $P < 0.001$; $se_c = 3.05$; Fig 5).

The weighted mean dry bulb temperature was related to the cockpit db as follows:

$$\overline{T}db_W = 1.71 + 0.90\ T_{db} \tag{17}$$

($0.40 \leqslant r^2 \leqslant 0.86$ for 5 sorties; $se_m = 0.06$, $P < 0.001$; $se_c = 2.57$; Fig 5).

Individual measurements of T_{db} at different levels in the cockpit showed a vertical gradient, the legs being cooler than the chest. The maximum gradient recorded from calf to chest was 14^o; the maximum thigh to chest gradient was 8^o.

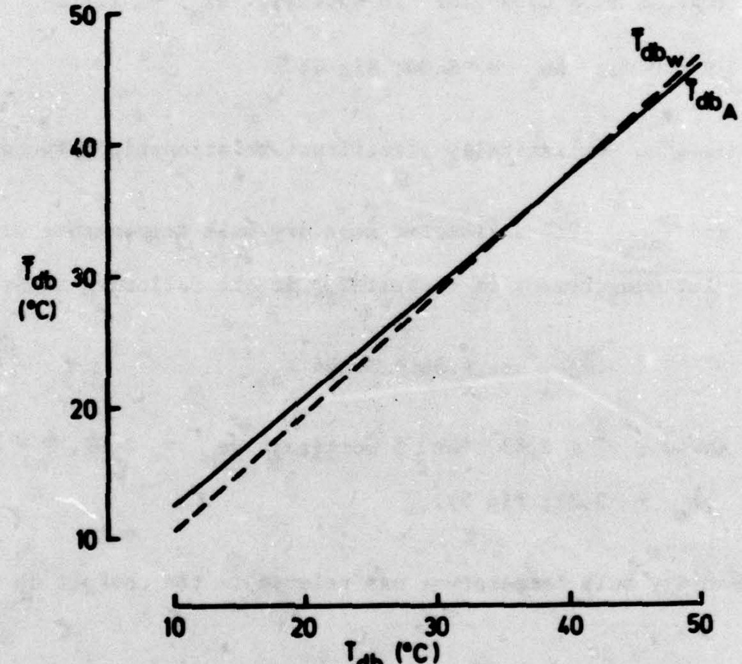

Figure 5 Relationship between single point and multiple point measurements of cockpit T_{db}.

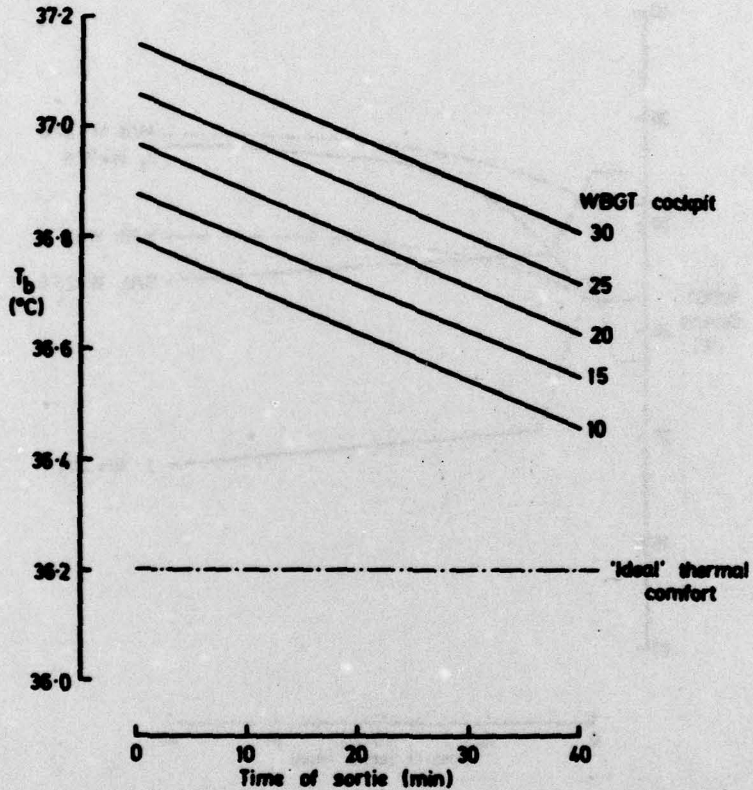

Figure 6 Prediction of pilot T_b during a sortie at different levels of cockpit WBGT.

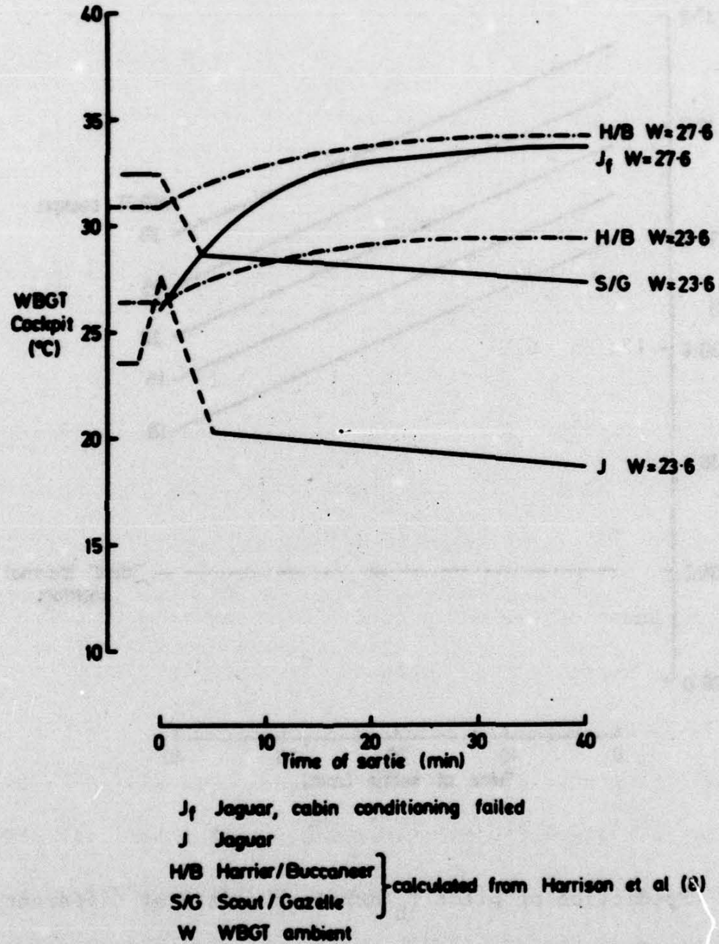

Figure 7 Comparison of predicted cockpit *WBGT* during sorties in Jaguar, Harrier/Buccaneer and Scout/Gazelle aircraft at the same level of ambient WBGT.

DISCUSSION

Harrison et al (7) found that ambient WBGT correlated significantly with both cockpit WBGT and pilot T_b in Harrier and Buccaneer aircraft, and were able to predict cockpit WBGT during sorties for different ambient WBGT levels. In the Jaguar, however, no relationship between ambient conditions and cockpit or pilot temperatures could be demonstrated. Consequently, it was not possible to predict pilot thermal strain or cockpit thermal stress from ambient WBGT. However, prediction of pilot thermal strain has proved possible provided that cockpit WBGT is known (Figure 1) and this can be related to sortie time (Figs 2 and 3) as follows:

$$T_b = 36.62 + 0.017\ WBGT_{cockpit} - 0.0085\ t \qquad (18)$$

($0.42 < r^2 < 0.97$ for 13 sorties; se_m (WBGT) = 0.004, $P < 0.001$; $se_m(t) = 0.0026$, $P < 0.01$; $se_c = 0.12$; Fig 6).

Equation 18 allows prediction of pilot thermal strain with greater accuracy than equation 9.

The effectiveness of the cabin conditioning systems of different aircraft may be compared in terms of the slopes of the equations describing the relationship between cockpit WBGT and T_b as in Table 1. The differences in intercept between the equations probably reflect the pilot's response to differences in the initial ambient temperatures and other preflight conditions. (The mean ambient WBGT for the Harrier/Buccaneer trial was 20.5°C (7); for this trial it was 23.6°C; and for the one sortie with cabin conditioning failure, it was 27.6°C.) It can be seen that conditions in the Jaguar with the failed cabin conditioning changed in a very similar way to the Harrier (Table 1 and Fig 7). The effectiveness of the various cabin conditioning systems is also indicated in Fig 7 which provides a comparison of data from this trial with the prediction made by Harrison et al (7) for the Harrier/Buccaneer combined and the Scout/Gazelle combined, at the same level of ambient

TABLE 1

Rate of Rise of T_b with Cockpit WBGT

Aircraft	Source	Slope
Jaguar	This trial	0.033
Jaguar with failed cabin conditioning	This trial	0.051
Harrier	Harrison et al (7)	0.049
Buccaneer	Harrison et al (7)	0.129

WBGT. The differences in initial cockpit WBGT between aircraft types reflect the different times before take-off that the canopies were closed. The Harriers and Buccaneers tended to have their canopies closed about 15 min before take-off; consequently, cockpit temperatures increased substantially over ambient levels (for example, 6). On the other hand, the Jaguar aircraft at Decimomannu were parked with their canopies open and cockpit WBGT did not rise until the canopies were closed just before take-off.

The differences in the way cockpit WBGT changes with time in the different aircraft are explained as follows. After take-off, cabin temperatures change towards an equilibrium temperature at which heat gain is balanced by heat loss. This temperature will depend mainly on the flight profile (speed and altitude), the ambient environmental conditions, the electrical heat load in the cockpit and the performance of the conditioning system. If these factors are constant, cockpit temperature will rise or fall depending on its starting value. In practice, equilibrium temperatures are hardly ever reached because of changing heat input and extraction and because of limited sortie duration.

The evidence from this and the previous studies suggests that the equilibrium temperature for the Jaguar is about 10^{o} lower than for the Harrier and Buccaneer at comparable speed, altitude and ambient conditions. This is almost certainly due to Jaguar's much more effective cabin conditioning system. Thus the WBGT in this trial fell towards its equilibrium temperature but the Harrier/Buccaneer rose towards their equilibrium temperature. Both changes are probably exponential, but the steep part of the change in the Jaguar is lost in the gap between early data points. Increasing the mass flow of cabin air lowers the inlet temperature, decreases heat pick-up in transit through ducts and cockpit and increases air flow over the pilot. An inverse relationship between airflow and WBGT is therefore to be expected (Fig 4). From this, it follows that the slope of the relationship between cockpit WBGT and sortie time will be determined by the mass flow and inlet temperature of the conditioning air and also by the difference between the cockpit temperature and the theoretical equilibrium temperature for the flight conditions. The intercept of this relationship is obviously unrelated to starting conditions; rather it reflects the asymptote (or equilibrium temperature) of the exponential relationship between cockpit WBGT and sortie time, and this will be determined also by the performance of the cabin conditioning system.

It can be seen that, despite an effective cabin conditioning system, pilots flying the Jaguar aircraft in summer conditions are generally above the ideal level of thermal comfort, although the conditions did not approach those regarded as dangerous by Nunneley et al (9). No core temperature (T_{ac}) above 38.0°C was measured during the trial, although it was equalled on several occasions. Skin temperatures approaching the same level were seen only in the sortie where cabin conditioning failed. At these skin and core temperatures, there is laboratory evidence of motor performance decrement (2, 3); dehydration of up to 1% was also encountered, and this has been described as causing a decrement in physical work capacity (11). It should be noted that aircrew in this trial wore light,

summer, aircrew equipment assemblies. It would obviously be anticipated that the wearing of more insulative garments will increase the thermal strain on the pilot.

The data also demonstrated a vertical gradient in dry bulb temperature in the cockpit similar to that described for the F4 aircraft (1). The results confirmed the bias reported by Allan et al (1) in the use of a single point measurement of T_{db} in the cockpit at shoulder height compared to a mean environmental $\overline{T}_{db}$ derived from equation (2). This bias was found to be smaller in the Jaguar than the 4^oC found in the F4, and was less than 2^o between 20 and 40^oC. The data for the Jaguar also showed that there was little to be gained in relating $\overline{T}_{db}$ to body surface area because an arithmetic mean was just as accurate (Fig 5); in the temperature range of 20-40^oC, however, the single measurement of T_{db} at the pilot's shoulder is probably sufficiently accurate.

ACKNOWLEDGEMENTS

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